

Hungaria region as possible source of Trojans and satellites in the inner solar-system.

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ABSTRACT

The Hungaria Family (the closest region of the Main Belt to Mars) is an important source of Planet-Crossing-Asteroids and even impactors of terrestrial planets. We present the possibility that asteroids coming from the Hungaria Family get captured into co-orbital motion with the terrestrial planets in the inner solar system. Therefore we carried out long term numerical integrations (up to 100 Myr) to analyze the migrations from their original location - the Hungaria family region- into the inner solar system. During the integration time we observed whether or not the Hungarias get captured into a co-orbital motion with by the terrestrial planets. Our results show that 5.5 % of 200 Hungarias, selected as a sample of the whole group, escape from the Hungaria region and the probability from that to become co-orbital objects (Trojans, satellites or horseshoes) turns out to be $\sim 3.3\%$: 1.8% for Mars and 1.5% for the Earth. In addition we distinguished in which classes of co-orbital motion the asteroids get captured and for how long they stay there in stable motion. Most of the escaped Hungarias become Quasi-satellites and the ones captured as Trojans favour the L_5 lagrangian point. This work highlights that the Hungaria region is a source of Mars and also Earth co-orbital objects.

Key words: celestial mechanics – minor planets, asteroids – Solar system: general – methods: numerical

1 INTRODUCTION

A co-orbital configuration refers to a celestial object (such as an asteroid) that keeps a quasi-constant distance from its parent object (in this work, planet) and it is on a 1 : 1 mean motion resonance (MMR). In this configuration the asteroid has a rotational period around the Sun similar to the planet which is co-orbiting.

The co-orbital bodies are subdivided in classes of objects which depend on their point of libration. In this study we are interested in the following classes for the Inner solar system: (a) Trojan objects, which librate around one of the two stable Lagrangian equilibrium points, L_4 and L_5 , respectively asteroids leading (libration angle $\lambda \sim +60^\circ$) and heading ($\lambda \sim -60^\circ$) the planets orbit, i.e. 2010 TK₇ for the Earth (Connors, Wiegert & Veillet 2011) and (b) Satellites (MOs) and quasi-satellites (QSSs) orbits, which librates around 0° , but the libration width σ is much larger for the QSSs (more details are presented in Section 2). In contrast to MOs, QSSs orbits lie outside the planet's Hill sphere,

therefore they are not long-term stable. Over time they tend to evolve to other types of resonant motion, where they no longer remain in the planet's neighborhood.

Currently one Earth Trojan and 9 Martian Trojan asteroids, 5 horseshoe objects (one Martian and 4 of the Earth) and also 6 quasi satellite close to the Earth, are known. All known co-orbital objects – including candidates – in the inner solar system are presented in Tab. 1. Theoretical studies predict that Trojan asteroids are a byproduct of planet formation and evolution and were later captured from the planets. Chaotic capture of Jovian Trojan asteroids in the early Solar System (~ 3.4 My), were presented in the work of Morais & Namouni (2013). Lykawka et al. (2009) and Lykawka & Horner (2010) investigated the origin and dynamical evolution of Neptune Trojans during the formation and migration of the planets. They found that the captured Trojans display a wide range of inclinations ($0^\circ \lesssim i < 40^\circ$). These results were confirmed by Schwarz & Dvorak (2012), who investigated the capture probability of co-orbital objects for the planets Venus, Earth and Mars.

Early work on the origin of NEAs (e.g. Greenberg & Nolan 1989, 1993), suggested that colli-

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sions in the main-belt continuously produce new asteroids by fragmentation of larger bodies. These fragments can be injected into the ν_6 and J3:1 MMR with Jupiter, which causes a change of their eccentricities and brings them into orbits intersecting the orbits of Mars (Mars crossers) and/or Earth (Earth crossers, e.g. Milani et al. 1989): gravitationally, the NEAs are transported first to Mars, mainly by MMRs, three-body mean motion resonances (3BMMRs, for a description of this kind of resonances see Nesvorný & Morbidelli 1998) and secular resonances (SRs), and then to other more interior planets due especially to close encounters with Mars. Also non-gravitational forces can play a role in the transportation as was shown by Bottke et al. (2002, 2006); Greenstreet, Ngo & Gladman (2012) and Čuk, Gladman & Nesvorný (2014), but as a first stage we will take into account only gravitational forces in this work and the Yarkovsky effect will be considered in a future work.

In order to describe the primordial main belt before the LHB, a hypothetical inner extension of the main belt¹, has been suggested and dubbed the “E-belt” (Bottke et al. 2012). One motivation for this inference is to provide a source for basin-forming lunar impacts of the LHB. These E-belt asteroids were supposed to have a semi-major axis ranging from 1.7 to 2.1 au. Prior to the giant planet migration described in the Nice model, these asteroids would have been in a more stable orbit, with the ν_6 secular resonance outside the border of this region (Morbidelli et al. 2010) with the outer giant planets having a more compact configuration with an almost circular orbit (Gomes et al. 2005). Then, during the migration of the giant planets (Minton & Malhotra 2011), the ν_6 and other related resonances would have destabilized the E-belt population. Most of them would have moved inward onto terrestrial planets as their eccentricities and inclinations increased making impacts with the planets and so some of these asteroids (0.1-0.4 %) would have acquired orbits similar to the Hungarias. In this sense, the Hungarias are supposed to be a remnant of the E-belt; the survivors of the E-belt dispersion (Bottke et al. 2012). This idea is a development of the NICE model (see in particular Morbidelli et al. 2010) and it should make it more consistent. The NICE model has still some gaps, the most important are: (a) it does not explain the presence of Mercury and (b) the rate of the incoming comets and even an explanation of the large-scale mixing of reddish and bluish material (from the photometric point of view) in the asteroid belt (DeMeo & Carry 2014). For this reason we study in this work only the present Hungaria group, which might be an evolution of the ancient E-belt.

The importance of considering Hungarias as source of NEAs (which can originate also possible co-orbital bodies of terrestrial planets), is shown very well in Galiazzo, Bzszó & Dvorak (2013a) and in Čuk, Gladman & Nesvorný (2014), who described the dynamical evolution of these mainly E-type asteroids (Carvano et al. 2001; Assandri & Gil-Hutton 2008; Warner et al. 2009) into the NEAs region.

Table 1. All observed Earth and Mars co-orbital asteroids. * depicts an object which is only a candidate. The different motion types are horseshoe orbits *H* and tad-pole orbits in Lagrangian points L_4 and L_5 or in both of this last two consecutively, like jumping Trojans *JT*. T_j represents the Tisserand parameter in respect of Jupiter and *MT* stands for motion type.

Name	a [au]	e	i [°]	T_j	MT
Mars					
(121514) 1999 UJ ₇	1.5245	0.039	16.8	4.449	L_4
(5261) Eureka	1.5235	0.065	20.3	4.428	L_5
(101429) 1998 VF ₃₁	1.5242	0.100	31.3	4.334	L_5
(311999) 2007 NS ₂	1.5237	0.054	18.6	4.439	L_5
(269719) 1998 QH ₅₆ *	1.5507	0.031	32.2	4.279	L_5
(385250) 2001 DH ₄₇	1.5238	0.035	24.4	4.400	L_5
2001 SC ₁₉₁	1.5238	0.044	18.7	4.439	L_5
(88719) 2011 SL ₂₅	1.5238	0.115	21.5	4.415	L_5
2011 UN ₆₃	1.5237	0.064	20.4	4.427	L_5
(157204) 1998 SD ₄	1.5149	0.125	13.7	4.475	<i>H</i>
Earth					
2010 TK ₇	1.0000	0.191	20.9	6.008	<i>JT</i>
(3753) Cruithne	0.9977	0.515	19.8	5.922	<i>QS</i>
(164207) 2004 GU ₉	1.0013	0.136	13.7	6.041	<i>QS</i>
(277810) 2006 FV ₃₅	1.0013	0.378	7.1	6.003	<i>QS</i>
2003 YN ₁₀₇	0.9987	0.014	4.3	6.132	<i>QS</i>
(54509) YORP	1.0060	0.230	1.600	6.028	<i>QS</i>
2001 GO ₂	1.0067	0.168	4.620	6.033	<i>QS</i>
2013 BS ₄₅	0.9939	0.084	0.773	6.106	<i>H</i>
2010 SO ₁₆	1.0019	0.075	14.5	6.041	<i>H</i>
2002 AA ₂₉	0.9926	0.012	10.8	6.100	<i>H</i>
2006 JY ₂₆	1.0100	0.083	1.4	6.030	<i>H</i>
(85770) 1998 UP ₁ *	0.9983	0.345	33.2	5.901	<i>H</i>

Here we perform a numerical study on the orbits of the asteroids of the Hungaria Family (see also Galiazzo, Bzszó & Dvorak (2013a)), investigating their capture probability into the 1:1 MMR with the terrestrial planets: Venus, Earth and Mars. Hungarias are relatively far out away from the orbit of the terrestrial planets, in fact the inner part starts with a semi-major axis equal to 1.78 au (Galiazzo, Bzszó & Dvorak 2013a). To study the capture of the Trojan asteroids into the inner Solar System it is necessary to consider the interactions (collisions and mass transport) between the Near-Earth-Asteroids (NEAs) and the main-belt asteroids.

During the integration time we observe whether or not the Hungarias get captured into a co-orbital motion with the planets in the inner Solar-system, from Venus to Mars. In addition we distinguish in which classes of co-orbital motion the asteroids get captured and for how long they stay there in stable motion. Therefore we carry out long term numerical integrations up to 100 Myr to analyze the transfers from their original location - the Hungaria family region- towards the terrestrial planets.

The paper is organized as follows: the model and the methods are described in Section 2; the results are shown in Section 3 (subdivided in two subsections, subsection 3.1, where we describe some sample cases of Hungaria orbital evolution and transport mechanism and subsection 3.2, where we give the probability for an Hungaria to get in co-orbital motion

¹ The primordial main belt before the Late Heavy Bombardment (LHB) event

with a terrestrial planet, its lifetime and orbit in such configuration). The conclusions are in Section 4.

2 MODEL AND METHODS

We do numerical N-body simulations using the Lie integration method (Hanslmeier & Dvorak 1984; Eggl & Dvorak 2010; Schwarz & Dvorak 2012; Galiazzo, Bazsó & Dvorak 2013a). We continue the last work of Galiazzo, Bazsó & Dvorak (2013a) considering the calculations of the Hungaria group: we take a sub-sample of 200 bodies, representative of the whole group, as the most evolved ones, selected out of the total sample of 8258 asteroids² considering a criterion based on the osculating elements. We choose the following variable $d = \sqrt{\left(\frac{a}{\langle a \rangle}\right)^2 \left(\frac{e}{\langle e \rangle}\right)^2 \left(\frac{\sin i}{\langle \sin i \rangle}\right)^2}$ and picked up 200 Hungarias with the highest values of d . Therefore first we integrate the orbits to the asteroids of the Hungaria group as defined in Galiazzo, Bazsó & Dvorak (2013a)³.

Then, after the first integration, 11 fugitives out of 200 are detected and therefore they are again dynamically investigated. For any fugitives, 49 clones were generated: random values for (a, e, i), beginning with the escapers' initial conditions in the following ranges: $a \pm 0.005$ (au) $e \pm 0.003$ and $i \pm 0.005^\circ$.

The model for the solar system is now from Venus to Saturn and the integration time is once more 100 Myr. Finally we search for captures with the terrestrial planets (Venus, Earth and Mars).

Whenever we find a capture, we integrate again the orbit of the asteroid from the point when they get captured. We perform another integration (with the same simplified solar system) with a smaller⁴ time step (100 d) for 20 kyr and studying the orbit in detail.

The aim of this work is to study the capture of Hungaria asteroids in the Inner solar system, in particular for 2 different types of captures: 1) Satellite orbits and 2) Tadpole orbits (L_4 and L_5). In some cases we find Horseshoes orbits and jumping Trojans⁵, too.

The classification was done by the help of the libration width σ , which is defined as the difference between the mean longitude of the asteroid and the planet (Venus, Earth or Mars) ($\lambda - \lambda_P$). λ , λ_P are given by $\lambda = \varpi + M$, $\lambda_P = \varpi_P + M_P$ were ϖ , ϖ_P are the longitudes of the asteroid

² The orbital data are taken from the ASTORB database (<http://www2.lowell.edu/elgb>)

³ The Hungaria group is defined in this region of osculating elements: $1.78 < a[\text{au}] < 2.03$, $12^\circ < i < 31^\circ$ and $e < 0.19$. A sub-sample of 200 bodies representative of the Hungaria group are integrated in a simplified Solar System (Sun, Mars, Jupiter, Saturn and the mass-less asteroids), for 100 Myr to identify possible escapers, like Galiazzo, Bazsó & Dvorak (2013a).

In fact analyzing the orbits of the clones of 3 Hungarias (100 clones per asteroid) next to resonances with the Earth and Venus (i.e. V1:4 and E2:5); including also these 2 planets in the integrations, we found only one important deflection out of 300 bodies.

⁴ The first integration, where the Hungaria orbits were computed for 100 Myr, had a time step of 1000 years

⁵ Asteroids which jump from L_4 to L_5 or vice versa (Tsiganis, Dvorak & Pilat-Lohinger 2000)

Asteroid	a [AU]	e	i [deg]
(211279) 2002 RN ₁₃₇	1.8538	0.1189	22.82
(152648) 1997 UL ₂₀	1.9894	0.1841	28.88
(141096) 2001 XB ₄₈	1.9975	0.1055	12.32
(24883) 1996 VG ₉	1.8765	0.1556	22.71
(41577) 2000 SV ₂	1.8534	0.1843	24.97
(175851) 1999 UF ₅	1.9065	0.1874	19.24
(39561) 1992 QA	1.8697	0.1116	26.2
(41898) 2000 WN ₁₂₄ *	1.9073	0.1062	17.11
(30935) Davasobel*	1.9034	0.1178	27.81
(171621) 2000 CR ₅₈ *	1.9328	0.1051	17.19
(129450) 1991 JM*	1.8512	0.1263	24.50

Table 2. Osculating elements for the escaping Hungarias: semi-major axis (a), eccentricity (e), inclination (i) in degrees; data taken from the database “astorb.dat”. These 7 asteroids also belong to the Hungaria family (see astdys website, <http://hamilton.dm.unipi.astro.it/astdys/>, for comparisons with the elements), so we can treat the fugitives restrictively also as member of the Hungaria family. * means they are not candidate HCOs.

and of the planet and M , M_P are the mean anomaly of the asteroid respectively of the planet.

In a next step we compared the distributions of the orbital elements a , e , and i . We also examine the orbital histories of captured objects to determine type of capture and the orbital evolution of objects before and after a capture event.

3 HUNGARIA CO-ORBITAL OBJECTS (HCOs)

There are 7 candidates (out of 11) among the Hungaria fugitives in Galiazzo, Bazsó & Dvorak (2013a) which can be captured in to co-orbital motions with terrestrial planets, the initial condition can be found in Table 2.

Among all the Hungaria fugitives we found co-orbital objects (from now on HCOs), like tadpole orbits (L_4 and L_5), MOs, QSSs and some horseshoe orbits, too.

3.1 Sample cases of a Trojan and of a Quasi-satellite

We analyse the orbital evolution of the fugitive clones, observing whether they get captured in to co-orbital motion with terrestrial planets. We have to mention that we never find a case where an asteroid get captured by Mars and then by the Earth together and there is no case for Venus co-orbital motion. We find several cases of QSSs, i.e. for a clone of (141096) 2001 XB₄₈⁶ (see the graphics description in Fig. 1 and 2), but also some jumping Trojans.

3.1.1 Orbital evolution of a typical HCO and transport mechanism

There are different possibilities how the clones get captured into co-orbital motion, an example of a capture into co-

⁶ several clones of different asteroids goes in co-orbital bodies and several ones of 2001 XB₄₈ become QSSs

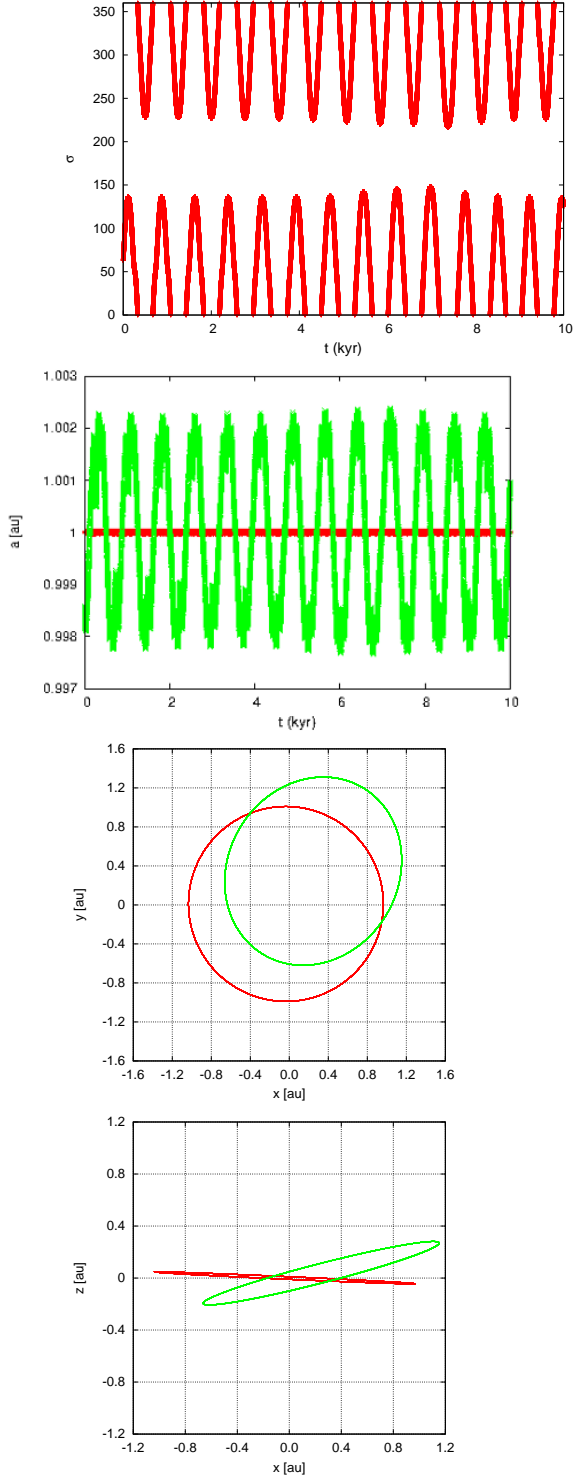


Figure 1. From top to bottom: 1) Libration angle (σ) of the Earth QS (141096) 2001 XB₄₈; 2) the semi-major axis of the asteroid librating around the one of the Earth; 3) views of the orbits of Earth (curve with a radius of 1 au) and a clone of the asteroid 2001 XB₄₈ (captured by the Earth for about 10 kyr) as seen from above the north ecliptic pole in the geocentric plane, emphasizing the eccentric orbit of this quasi satellite; 4) Views of the orbits of the bodies of point (3) seen on the plane perpendicular to the ecliptic. The inclined orbit of the asteroid to the Earth is clear, allowing excursions of roughly 0.2 and 0.3 au above and below the plane.

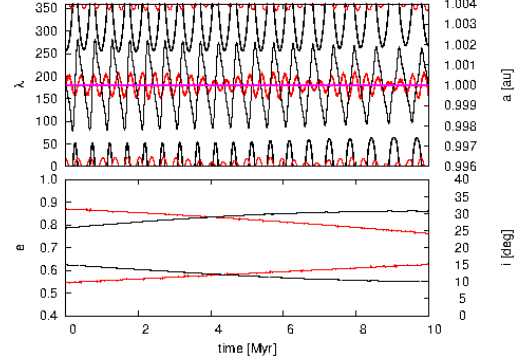


Figure 2. Comparison between a terrestrial satellite and a Quasi-satellite. In the upper panel the critical angle (upper and bottom curves) versus time is represented and the semi-major axis variation (central curves, apart the horizontal line which represents the semi-major axis of the Earth) versus time again. Lower panel represents eccentricity and inclination versus time of the 2 different types of co-orbital bodies. The configurations represent the satellite-state of 2001 XB₄₈ (lighter color) and quasi-satellite state (darker color) in co-orbital motion with the Earth.

orbital motion is the candidate 2002 RN₁₃₇. The description of the orbital evolution of one of its clones can help us to understand the co-orbital evolution of the HCOs. A clone of 2002 RN₁₃₇ becomes a satellite of Mars after 73.237 Myr of integration and it stays like this for 6.5 kyr. We check its orbital evolution:

- The close encounters, which change significantly the orbit of the asteroid and consequently its osculating elements, but in particular the semi-major axis. As shown in Tab. 1 the Hungaria fugitives have larger inclinations (in comparison with the initial conditions of the asteroid families in the main belt), which will lead to an escape from that region, because of SRs, and later on to close encounters with the terrestrial planets (e.g. Mars or the Earth). In general this fact increases the possibility that the asteroid get captured into co-orbital motion. This was also shown for different initial conditions by Schwarz & Dvorak (2012). The Hungaria candidate 2002 RN₁₃₇ represents the orbital behavior which we described previously. This decrease of the inclination favors the capture into co-orbital motion with Earth. Fig. 3 let us see multiple close approaches to Mars and after that also to the Earth. In the time-span between about 55 Myr and 65 Myr of integration, many close encounters are found, thus the inclination change dramatically and that leads to the Earth asteroids capture: the orbital elements of the captured asteroid lies in the stability window for that planet as shown by Tabachnik & Evans (2000).

- The resonances: MMRs, 3BMMRS and SRs, which change the eccentricity and again the inclination. An example of the most important resonances for this case are visible in the evolution of one of our fugitives: from about 25 Myr to 30 Myr, g_5 is active. The asteroid is inside the region of influence of this secular resonance (upper panel of Fig. 4), having the inclination between $i \sim 24^\circ$ and $i \sim 32^\circ$ and keeping its semi-major axis between 1.9 au and 2.0 au. Then the asteroid travels into the regions of influence of the SRs g_3 and g_4 (see also Warner et al. 2009; Milani et al. 2010, , where these regions are well described) from about

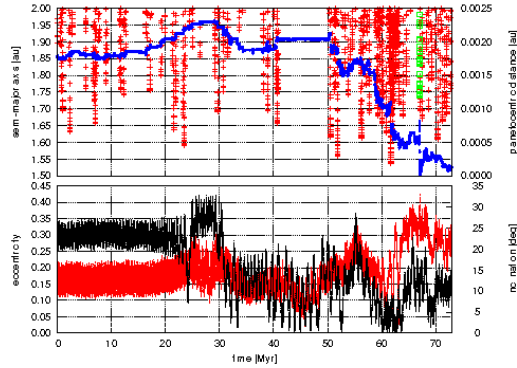


Figure 3. Evolution of the orbit till the initial instant of co-orbital motion. Upper panel: semi-major axis and Planetocentric distance versus time for a clone of the asteroid 2002 RN₁₃₇. In vertical points in crosses and dot-quadrates, close encounters with respectively: Mars and the Earth. Bottom panel: eccentricity (light color) and inclination (black).

34 Myr and 38 Myr, where it does not have close encounters (Fig. 3, upper panel and 4, bottom panel).

The strongest MMRs and 3BMMrs which influence the orbit of this Hungaria appear to be: initially S12:1 and J13-S9-2 (where J is for Jupiter, S for Saturn and the last number is for the asteroid), J20-S15-3 and J13-S10-2 (Fig. 5). Then from 20 Myr to about 22 Myr, the first order 3BMMR J13-S10-2 is active on the asteroid. More over J19-S15-3 acts together with the g_5 for about 5 Myr from 25 Myr to 29.5 Myr and, from 29.5 Myr to about 30.5 Myr, we have J6-S4-1. From about 40 Myr to 50 Myr, M5:7, then from 51 Myr to 52 Myr, J5-S1-1 and in the end between 59 Myr and 66 Myr, when there are no close encounters, in chronological order M11:13 and J16:13 (for 2 Myr), E2:1 (for 1 Myr) and J17-S14-2 (for about 1.5 Myr). All these resonances change significantly the eccentricity and the inclination facilitating close encounters of the asteroid with the planets and thus contributing to the change of osculating elements, in favor of some possible co-orbital orbit.

3.2 Sources of co-orbital bodies (results)

3.2.1 Population distributions

We find that 3.3 % of all the clones of all the fugitives (11) become HCOs: 1.8% for Mars and 1.5% the Earth, see Tab. 3 for the distribution of the different classes and Tab. 4 for the probability of becoming an HCO for each single Hungaria fugitive. This percentage⁷ represents the capture probability which we calculate from the total number of clones (a summary for the different co-orbital classes are given in Tab 3). We obtain more Hungaria co-orbital bodies for Mars compared to those of the Earth, even if the difference is not so significant and many escapers experience different types of co-orbital motions. The QS class turns out to be the most favorable type of co-orbital motion.

⁷ The percentage is the total number of co-orbital bodies per planet divided the total number of asteroids (clones) integrated per region times 100, in this way we can compare better the 2 results.

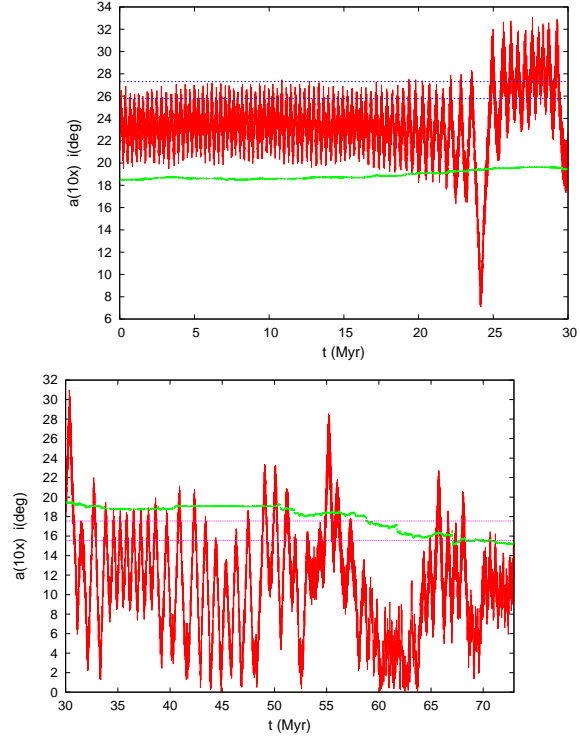


Figure 4. Dynamical evolution of a clone of the asteroid 2002 RN₁₃₇ later captured by Mars. The 2 horizontal lines of the upper panel represent approximately the region of influence of the secular resonance g_5 for that value of semi-major axis between 25 Myr and 30 Myr. The 2 horizontal lines represent approximately the region of influence of the secular resonances g_3 and g_4 , for that value of semi-major axis between 34 Myr and 38 Myr. On the y-axis inclination in degree and semi-major axis in astronomical units times 10.

We find more Hungaria Trojans in L_5 than L_4 and this is what which was presently observed for real Trojans. We can conclude that 0.6% Hungaria fugitives get captured in L_4 and 1.1% in L_5 for Mars; for the Earth, 0.4% Hungaria fugitives get captured in L_4 and 0.6% in L_5 .

Also a few cases of Hungaria Jumping-Trojans are found and usually the Hungaria Jumping-Trojans stay in this condition for longer times. The maximum life is for a clone of 2002 RN₁₃₇, whose life-time is 58 kyr (see also Fig 6).

Some fugitives have the probability to become an HCO only for a single planet, i.e. 2001 XB₄₈ and 1996 VG₉ for the Earth or 1997 UL₂₀ and 1999 UF₅ for Mars (Tab. 4).

The Hungarias with the highest probability to become a co-orbital asteroids have a probability of 8% to be so and they are 2002 RN₁₃₇ and 2000 SV₂. 2002 RN₁₃₇ is more likely to become a Mars HCO, the second one has both possibilities in equal measure (Mars or Earth HCO, Tab. 4).

Table 5 shows the distribution of asteroid captures (subdivided by inclinations and total number too) found in this work and we compare partly our result with the work of Schwarz & Dvorak (2012), “partly” because the initial conditions are different. The work of Schwarz & Dvorak (2012) considered the region of the NEAs that covers also a small part of the Hungaria region. They called it region C, which considered this range of semi-major axis: $1.54 \text{ au} < a < 2.20$

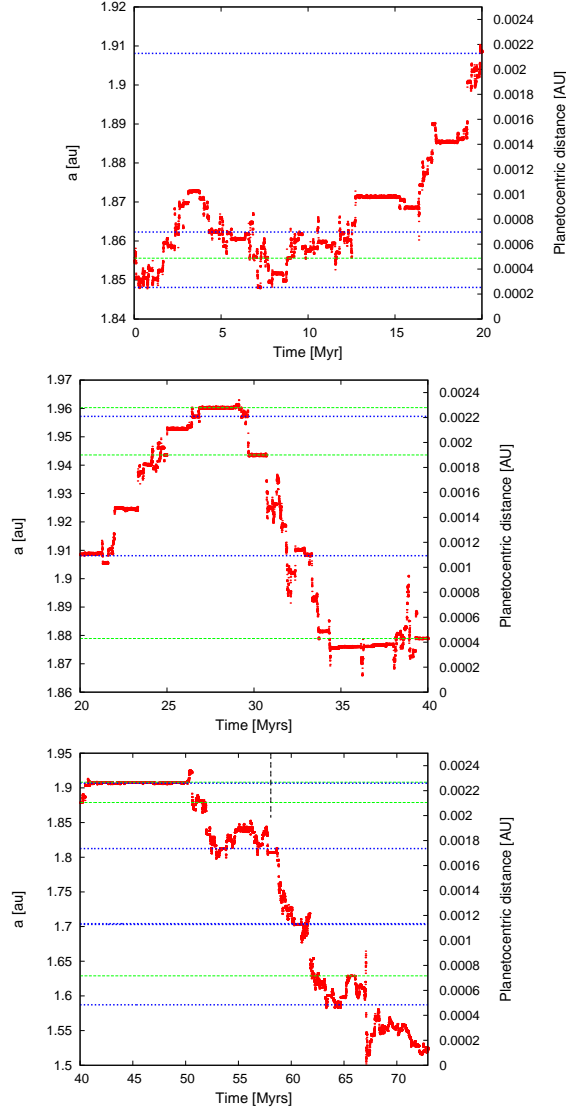


Figure 5. Resonances and close encounters: dynamical evolution of a clone of the asteroid 2002 RN₁₃₇ later captured by Mars, divided in 3 mains parts, from 0 Myr to 20 Myr, from 20 Myr to 40 Myr and then till 60 Myr, when the changes in the orbit are dominated only by close encounters and resonances have secondary importance. Position of the resonances: E2:1 = 1.5872 (it means a 2:1 resonance with the Earth is at 1.5872 au), J17-S14-2 = 1.6290 (it means a 17-14-2 3bodyMMR with Jupiter, Saturn and the asteroids centered at 1.6290 au), M11:13 = 1.7031, J16:13 = 1.7042, M3:4 = 1.8458, S12:1 = 1.8481, J13-S-9-2 = 1.8556, J20-S15-3 = 1.8623, J5-S1-1 = 1.8789, M5:7 = 1.9067, J13-S10-2 = 1.9081, J6-S4-1 = 1.9436, J13:3 = 1.9572, J19-S15-3 = 1.9603.

au, but only at certain inclinations and eccentricities (see Schwarz & Dvorak 2012).

However much less HCOs were found in the work of Schwarz & Dvorak (2012), compared to us. This is because only certain peculiar regions in orbital elements can drive asteroids in close approaches with terrestrial planets, and even more peculiar ones give rise to asteroids in co-orbital motions.

Table 3. Percentage of Hungaria captures in different classes (P. H.) from the total, average life time of the capture (\bar{t}_l). The * means that the total number of satellites is not equal to the sum of the total number of satellites and quasi satellites, because some clones can become Qs or satellites too, during their evolution.

Class	P. H. Earth	Mars	\bar{t}_l [ky] Earth	Mars
Satellites	0.6	0.6	7.5 ± 8.5	7.9 ± 7.1
Quasi-satellites	1.3	1.3	15.0 ± 9.7	7.0 ± 4.9
Satellites (Subtot*)	1.9	1.9	9.6 ± 1.6	9.0 ± 4.6
Trojans	1.1	1.1	7.9 ± 3.9	10.7 ± 4.4
Horseshoes	0.0	0.4	-	2.6 ± 1.5

Table 4. Relative probability of each fugitive to become HCO (Tot.) and for each planet in percentage.

Asteroid	Mars	Earth	Tot.
(211279) 2002 RN137	2	6	8
(152648) 1997 UL20	0	6	6
(141096) 2001 XB48	4	0	4
(24883) 1996 VG9	4	0	4
(41577) 2000 SV2	4	4	8
(175851) 1999 UF5	0	2	2
(39561) 1992 QA	4	2	6

3.2.2 Life time and orbits of the HCOs

The HCOs have a short lifetime (or libration period), a mean of ~ 10 kyr (9.6 kyr for the Earth and 9.0 kyr for Mars), with an exception for a jumping Trojan of 2002 RN₁₃₇, which stays in this condition for more than 50 kyr. However HCOs have lifetimes that usually range between 1 kyr and 20 kyr (Fig. 6). These results are in accordance with the life-time values found for real co-orbital asteroids, e.g. about 6.8 kyr for 2010 TK₇, a jumping-Trojan for the Earth, (Connors, Wiegert & Veillet 2011) or 1998 VF₃₁, an L₅ Mars Trojan, with a lifetime of 1.4 kyr (de la Fuente Marcos & de la Fuente Marcos 2012). These objects are usually transitional objects (with short dynamical life times) and the most stable HCOs have an inclination between $i = 10^\circ$ and $i = 17^\circ$, see also Fig. 6.

The Hungarias with smaller escape time from their original cloud have a shorter lifetime as co-orbital objects. In fact

Table 5. Captured asteroids from different region in percentage to the total. Regions are described in the text. C^- is for $i < 17^\circ$ and C^+ for $i > 17^\circ$. The numbers in the table are rounded to one digit. C is the region mentioned in Schwarz & Dvorak (2012) and H stands for HCOs at their initial conditions.

PLANET	C^-	C^+	C_{tot}	H^-	H^+	H_{tot}
Earth	0.0	0.0	0.0	0.0	1.5	1.5
Mars	0.1	0.0	0.1	0.0	1.9	1.9

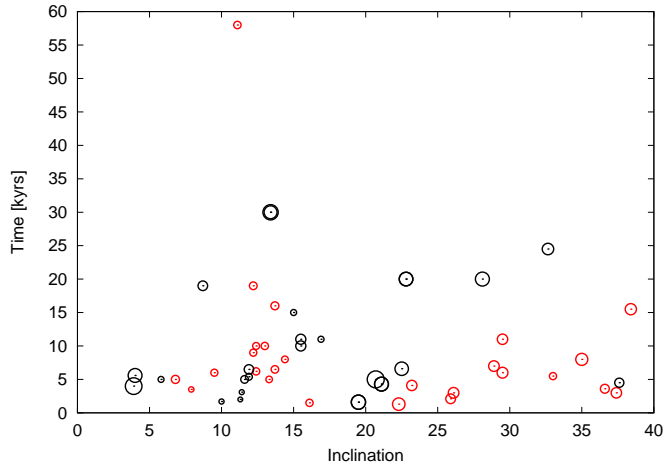


Figure 6. Life time in thousand years versus inclination in degree. Earth HCOs are black and Mars HCOs are lighter. The size of the points depends among their eccentricity. The most stable asteroid is a Martian HCO with $a=1.52368$, $e=0.3105$ and $i=11.11$ (a , semi-major axis, e , eccentricity and i , inclination).

the escape time (from the Hungaria region) decreases when they are perturbed by resonances, in particular SRs. This is the case of asteroid 2002 SV₂, that is injected very soon into the terrestrial planets due to the g_6 (Galiazzo 2013c). Three clones of 2000 SV₂ become QSs (1 for the Earth and 2 for Mars), e.g. one of them is captured very soon after 17.6 Myr of orbital evolution from initial conditions and it has its first close encounter with the Earth just at 10 Myr.

Our investigation shows many asteroids can have multiple-captures, but never with different planets. Many asteroids captured into HCOs can change their orbital behavior from QSs to tadpole orbits or into horseshoe orbits. The contrary is also possible, these multiple events was also found by Wiegert, Innanen & Mikkola (1998); Connors et al. (2002); Schwarz & Dvorak (2012). The switch of different types of co-orbital orbits happens especially for orbits with large eccentricity and/or high inclinations (and, as written before, Hungarias have these kind of orbits), having transitions from QS to horseshoe orbits (Namouni & Murray 1999), like 3753 Cruithne or 2002 AA29 (Brasser et al. 2004b), co-orbital objects for the Earth. For instance, we detect for the Hungarias a clone of 2002 SV₂ and one of 2001 XB₄₈ as transient co-orbital asteroids, see Fig. 7 and 8.

From the dynamical point of view the variation in semi-major axis of the Earth HCOs (from now on EHCs) is larger than the one of Mars by about more than $\frac{1}{3}$ times, see Table 6.

The inclination angles range from $\sim 3^\circ$ to very high inclined orbits, $\sim 40^\circ$. The range for the inclination of the EHCs is in accordance with past studies, in fact stability windows for Earth-Trojans are covered and no cases are found between $24^\circ < i < 28^\circ$. The inclination of the EHCs range on average between 15° and 18° and for Trojan $\sim 16^\circ$ (Table 7). Windows for Earth-Trojans, established by past works until now are: (a) $i < 16^\circ$, (b) $16^\circ < i < 24^\circ$ (Tabachnik & Evans 2000) and (c) $28^\circ < i < 40^\circ$ (Dvorak, Lhotka & Zhou 2012).

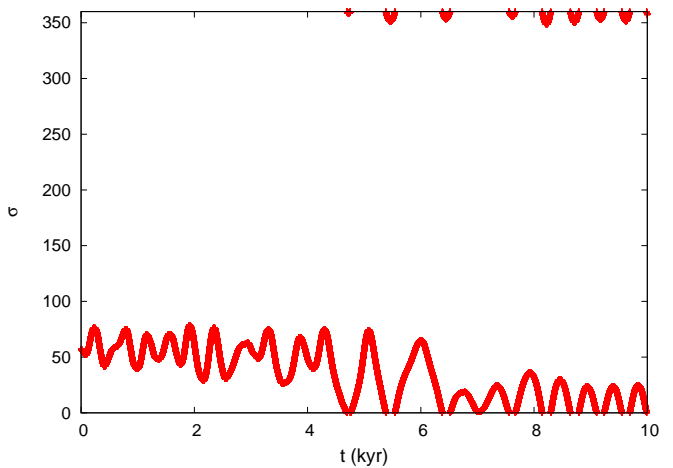


Figure 7. Transition from L_4 to a QS-state, for the asteroid 2001 XB₄₈. The y-axis is the libration amplitude and the time is in thousand years.

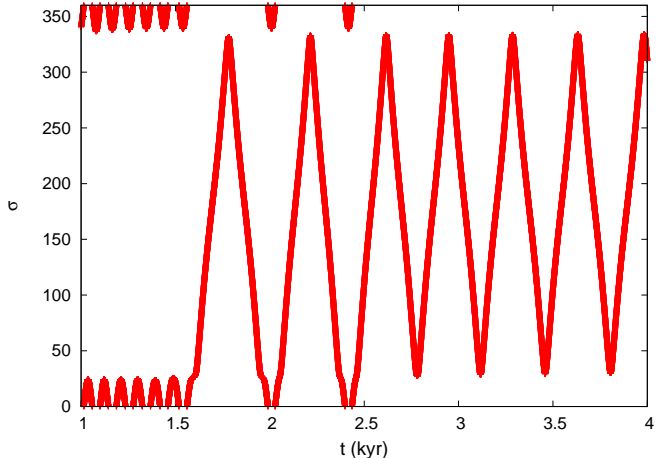


Figure 8. Transition from satellite of the Earth to an Horseshoe orbit, for the asteroid 2002 SV₂. The y-axis is the critical angle and the time is in thousand years from the initial state as HCO.

Mars HCOs (from now on MHCs) have in general high inclined orbits close to the original orbits, in fact they are less perturbed by close encounters compared to the EHCs. A remarkable thing is that the MHC satellites have less inclined orbits than other type of MHCs, see Table 7. The EHCs are usually less inclined than the MHCs, but the eccentricity is larger: $e_{EHC} \approx e_{MHC}/3$. The eccentricity of Mars and Earth tad-pole orbits are similar, about $\sim 0.32 < e < \sim 0.36$ on the average. The Earth Hungaria MOs have larger eccentricities than tad-pole orbits of both planets and also than MHC satellites (summarized in Table 7).

The Tisserand parameter⁸ (Table 7) shows different values for each kind of co-orbital objects, in general the T_j (J as Jupiter) of the QSs is usually higher. The typical

⁸ $T_{body} = (1/2a) + \sqrt{a(1-e^2)}\cos(i)$, where a is the semi-major axis of the asteroid orbit, e is the eccentricity and i is the inclination

Table 6. Dispersion in semi-major axis during co-orbital motion. Sat. = satellites, QSs = Quasi Satellites, Troj. = Trojans, hors. = horseshoe orbits, E = Earth and M = Mars. $\Delta_{1,M}$ = maximum dispersion in semi-major axis for Martian HCOs and $\Delta_{2,M}$ = minimum dispersion in semi-major axis for Martian HCOs. All measures are in units of 10^{-4} au.

Class	$\bar{\Delta}_E$	$\Delta_{1,E}$	$\Delta_{2,E}$	$\bar{\Delta}_M$	$\Delta_{1,M}$	$\Delta_{2,M}$
Sat.	17 ± 18	42	2	11 ± 7	19	5
QSs	26 ± 3	34	16	16 ± 3	22	11
Troj.	21 ± 7	29	7	13 ± 3	18	6
hors.	18 ± 2	19	17	-	-	-

Table 7. Orbital ranges for HCOs. EHCs = Earth Hungaria Co-orbital objects and MHCs = Mars Hungaria Co-orbital objects. \bar{T}_p and \bar{T}_j are respectively the Tisserand parameter relative to the planet in case (Mars and the Earth) and to Jupiter. \bar{a}_E = average semi-major axis for EHCs, \bar{e}_E = average eccentricity for EHCs and \bar{i}_E = average inclination for EHCs. Sat. = satellite, QSs = Quasi Satellites and Troj. = Trojans.

Class	\bar{a}_E [au] \bar{T}_j	\bar{e}_E \bar{T}_p	\bar{i}_E
Sat.	0.9999 ± 0.0011	0.431 ± 0.010	17.5 ± 0.9
	5.942 ± 0.007	2.687 ± 0.007	
QSs	1.0000 ± 0.0013	0.546 ± 0.012	15.4 ± 1.0
	5.912 ± 0.007	2.618 ± 0.004	
Troj.	1.0000 ± 0.0011	0.321 ± 0.004	15.8 ± 0.2
	6.010 ± 0.005	2.842 ± 0.001	
EHCs	1.0000 ± 0.0013	0.507 ± 0.011	16.1 ± 1.0
	5.923 ± 0.007	2.643 ± 0.005	
Class	\bar{a}_M [au] \bar{T}_j	\bar{e}_M \bar{T}_p	\bar{i}_M
Sat.	1.5236 ± 0.0006	0.331 ± 0.006	14.9 ± 0.7
	4.411 ± 0.002	2.842 ± 0.002	
QSs	1.5238 ± 0.0014	0.387 ± 0.015	20.3 ± 0.8
	4.374 ± 0.002	2.774 ± 0.005	
Troj.	1.5238 ± 0.0005	0.355 ± 0.010	20.8 ± 0.8
	4.381 ± 0.004	2.792 ± 0.006	
MHCs	1.5238 ± 0.0012	0.373 ± 0.012	22.1 ± 0.8
	4.362 ± 0.002	2.751 ± 0.006	

T_j of the EHCs ranges around $T_j = 5.923$ and it is higher than the one of the MHCs, $T_j = 4.362$. Then the Tisserand parameter compared to the relative planet (but also in respect to Jupiter) is higher for the MOs than the QSs.

Some real co-orbital objects of the terrestrial planets could be of Hungaria origin as shown in Tab. 1 and 7. We compare the osculating elements (the average ones during the libration life, Fig. 9 and 10) of the HCOs with the real co-orbital asteroids described in Table 1. The HCOs favor co-orbital bodies with large eccentricity and indicate that it could be possible to find co-orbital bodies for Mars and Earth at large inclinations too, even more than $i = 30^\circ$.

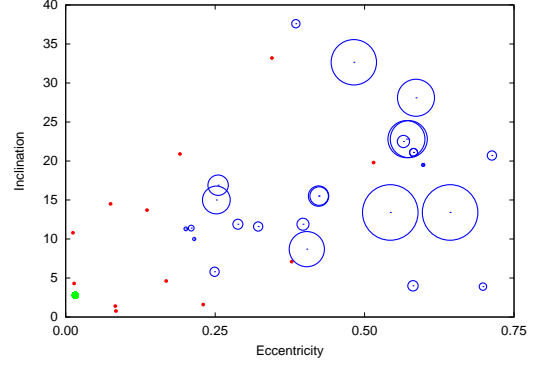


Figure 9. Average (during its co-orbital motion) orbital elements of the Earth HCOs in comparison with the real Earth co-orbital asteroids (circles with a dot inside): eccentricity versus inclination. The diameter of the circle is correspondent to their life time (only for the HCOs). Earth is represented by the largest dot with the least eccentricity and the least inclination.

This result – displayed in Fig. 9 and 10 – seems to assert that co-orbital bodies which have a range in inclinations of $5^\circ < i < 40^\circ$ and large eccentricities $0.22 < e < 0.53$ (even if most of the Mars HCOs are between 0.2 and 0.4) can be of Hungaria origin. The majority of the HCOs lie between $i = 5^\circ$ and $i = 17^\circ$. In this case the most probable former Hungarias are: Cruithne, 2006 FV₃₅, (85770) 1998 UP₁ and YORP for the Earth and, due to their inclination, 1999 UJ₇, 1998 VF₃₁ and 2011 SL₂₅ for Mars.

Concerning the physical characteristics of the known co-orbital bodies for terrestrial planets, some spectral type of these are known: for the Earth, Cruithne is a Q/S type⁹, YORP is S/V type (from TNEADB); for Mars, 1997 UJ₇ is an X type, 1998 VF₃₁ is an S type: Rivkin et al. (2003) says it is an S(I) type (angrite) and Rivkin et al. (2007) suggest also for a S(VII) type (achondrite similar to the spectrum of 40 Harmonia). So Cruithne and 1998 VF₃₁ can again still be considered as possible HCOs, because Hungarias have some S-type asteroids, not the majority, but still 17% (Warner et al. 2009) and especially 1997 UJ₇ which is an X-type asteroid like the majority of the Hungarias (Carvano et al. 2001; Warner et al. 2009), even if not specified for the sub-group Xe-type and further spectroscopic analysis would be needed.

Considering the size of the terrestrial planets' co-orbital bodies, we know the sizes which range from the very small 2013 BS₄₅ of about 10-40 m to Cruithne of about 3.3 km in approximate diameter, but usually they are less than 1 km, similarly to the standard range of the Hungarias.

⁹ From The Near-Earth Asteroids Data Base (TNEADB) at earn.dlr.de/nea/table1.new.html

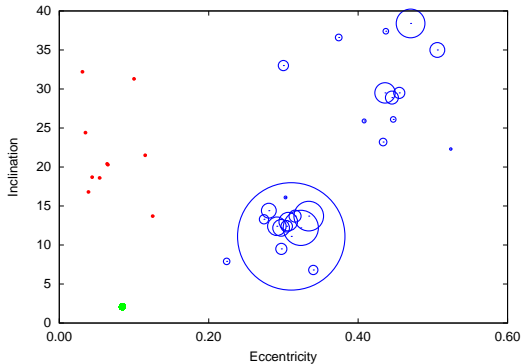


Figure 10. Average (during its co-orbital motion) orbital elements of the Mars HCOs in comparison with the real Mars co-orbital asteroids (circles with a dot inside): eccentricity versus inclination. The diameter of the circle is correspondent to their life time (only for the HCOs). Mars is represented by the largest dot with the least inclination.

4 CONCLUSIONS

The capture of Hungarias as Earth or Martian Trojans is not only due to the migration of planets, but also to migration of asteroids from the Main Belt, this is proved physically by Rivkin et al. (2003), who show that two Martian Trojans are collision fragments of a larger body. Numerically, this migration towards the terrestrial planet was described by Galiazzo, Bazsó & Dvorak (2013a), which emphasize the gravitational perturbations. Then, even Čuk, Gladman & Nesvorný (2014) show in particular the delivery of the aubrite meteorites by the Hungaria family, using also non-gravitational forces in the computation of the possible orbits.

The existence of HCOs have a low probability, 3.3% of all Hungaria fugitives, but nevertheless the contribution of the Hungaria region is important in order to give rise to co-orbital objects for terrestrial planets and so the Hungaria region is one of the source-regions of the Main Belt for this kind of bodies. The capture of possible co-orbital Mars objects, is about 1.8%, and for the Earth, it is 1.5% of the total amount of the clones of the Hungaria fugitives in 100 Myr of evolution. The Hungarias which have the highest probability (8%) to become co-orbital objects of terrestrial planets are 2002 RN₁₃₇ and 2000 SV₂. The first time they become co-orbital objects on average is at ~ 70 Myr after their orbital evolution from the original (present) position. The HCOs majority become QSs and concerning the former Hungarias captured into tad pole motions, they will be captured around L_5 . We found less captures for L_4 Trojans for both planets and we did not find any Venus HCOs, in agreement with the present observations. There are some cases of Jumping Trojans and with the longest life time, the maximum detected life time is 58 kyr. Also many HCOs behave like transitional co-orbital objects. Some Hungarias can become co-orbital objects of both planet together, i.e. 2000 SV₂ and some exclusively of only one like 1997 UL₂₀ and 1999 UF₅ of Mars and, 2001 XB₄₈ and 1996 VG₉ of the Earth.

The mechanism found in this work to transport the asteroids from the Hungaria region close to the terrestrial

planets and finally captured into co-orbital motion are the following ones:

(i) close encounters with Mars and Earth. Especially for the Earth case, the close encounters decrease the inclination in such a way that the Hungarias enter the window of stability for the Earth co-orbital objects as shown in Tabachnik & Evans (2000).

(ii) resonances: SRs, such as g_5 and g_6 ; MMRs such as M3:4, M11:13 and J16:13 and 3BMMRs, such as J13-S10-2 and J5-S1-1.

The average libration period of the HCOs is quite short ~ 10 kyr (9.6 kyr for the Earth and 9.0 kyr for Mars), in accordance with the real co-orbital objects of terrestrial planets, (e.g. 6.8 kyr for 2010 TK₇ Connors, Wiegert & Veillet 2011). Furthermore our investigations show that the Hungarias with the shortest lifetime are the first ones to escape from the Hungaria cloud, i.e. 2000 SV₂, Tab. 2.

Mars is the planet which captures more Hungarias, because of the shorter distance, even if the difference between Mars and the Earth capture probability is relatively small. Probably this can explain the smaller number of Earth co-orbital asteroids compared to Mars, because many asteroids will be captured by Mars (close encounters make the bodies achieving too large eccentricities to become Earth co-orbital bodies). However, the evolution of other families of the main belt in this sense should be studied in more detail in the future.

Concerning the HCOs' orbits, they range from $i \sim 3^\circ$ to $i \sim 40^\circ$. The EHCs average inclination range is $15^\circ < i < 18^\circ$ and for Trojans $i \sim 16^\circ$; this is in agreement with Schwarz & Dvorak (2012). The high inclined HCOs are favourable for MHCs instead of for EHCs and among the MHCs the satellites have the lowest inclined orbits (14.9°). The eccentricity of the EHCs is on average 3 times the one of the MHCs, only for the tad pole orbits, it is similar. The EHCs satellites have $e = 0.52$, and the Martians $e = 0.37$.

The typical Tisserand parameter with respect to Jupiters for EHCs is $T_j = 5.923$ and for MHCs is less, $T_j = 4.392$ and for satellites T_j is higher than the QSs.

Some real co-orbital asteroids have orbits which have a high probability to be former Hungarias, like Cruithne, (277810) 2006 FV₃₅, (85770) 1998 UP₁ and YORP for EHCs and (101429) 1998 VF₃₁ and, (88719) 2011 SL₂₅ for MHCs. In particular Cruithne and 1998 VF₃₁ have both orbital elements and physical characteristics typical of the S-type HCOs. Further investigations have to be done to look for the origin of present co-orbital objects of the terrestrial planets, both dynamical and observational studies. In the next work we will perform a new study for HCOs taking into account also non-gravitational forces.

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REFERENCES

- Assandri M. C. & Gil-Hutton R., 2008, *A&A*, 488, 339
- Barrabés, E., Mikkola, S., 2005, *A&A*, 432, 1115
- Bottke W. F., Morbidelli, A., Jedicke R., Petit J. M., Levison, H. F., Michel, P. & Metcalfe T. S. 2002, *Icarus*, 156, 399
- Bottke W. F., Vokrouhlický, D., Rubincam, D. P. & Nesvorný D. 2006, *Annu. Rev. Earth Planet. Sci.*, 34, 157
- Bottke W. F., Vokrouhlický D., Minton D., Simonson B. & Levison H. F. 2012, *Nature*, 485, 78
- Brasser, R., Innanen, K. A., Connors, M., Veillet, C., Wiegert, P., Mikkola, S., Chodas P. W., 2004b, *Icarus*, 171, 102
- Carvano J. M., Lazzaro D., Moth e-Diniz T., Angeli C., A. & Florczak M. 2001, *Icarus*, 149, 173
- Connors, M., Chodas, P., Mikkola, S., Wiegert, P., Veillet, C., Innanen, K., 2002, *Meteoritics & Planetary Science*, 37, 1435
- Connors, M., Wiegert, P., Veillet, C., 2011, *Nature*, 475, 481
- Čuk, M., Gladman, B. J. & Nesvorný, D., 2014, *Icarus*, 239, 154
- DeMeo, F. E. & Carry, B., *Nature*, 2014, 505, 629
- de la Fuente Marcos, C., de la Fuente Marcos, R., 2012, *MNRAS*, 432, L31
- Dermott, S.F., Murray, C.D., 1981, *Icarus*, 48, 12
- Dvorak, R., Pilat-Lohinger, E., Schwarz, R., Freistetter, F., 2004, *A&A*, 426, L37
- Dvorak, R., 2006, Freistetter et al. (eds.): *Proceedings of the 4th Austrian Hungarian Workshop on Trojans and related topics*, Eötvös University Press Budapest, 63
- Dvorak R., Schwarz R., 2005, *CeMDA*, 92, 19
- Dvorak, R., Schwarz, R., Süli, Á. and Kotoulas, T., 2007, *MNRAS*, 382, 1324
- Dvorak, R., Lhotka, Ch., Zhou, L., 2012, *Astron. Astrophys.*, 541, A127
- Eggl, S., Dvorak, R., 2010, *LNP*, 790, 431
- Galiazzo M. A., Bazsó, A., Dvorak, R., 2013a, *P&SS*, 84, 5
- Galiazzo M. A., 2013c, *PHd thesis*
- Gomes, R., Levison, H. F., Tsiganis, K., Morbidelli, A., 2005, *Nature*, 435, 466
- Greenberg, R. & Nolan, M., In: Binzel, R.P., Gehrels, T., Matthews, M.S. (Eds.), *Asteroids II. The University of Arizona Press, Tucson*, p. 778 (1989)
- Greenberg, R. & Nolan, M., In: Lewis, J., Matthews, M. S., Guerrieri, M. L. (Eds.), *Resources of near-Earth space. The University of Arizona Press, Tucson*, 473 (1993)
- Greenstreet S., Ngo H. & Gladman B. 2012, *Icarus*, 217, 355
- Hanslmeier, A., Dvorak, R., 1984, *A & A*, 132, 203
- Libre, J., Ollé, M., 2001, *A&A*, 378, 1087
- Lykawka P. S., Horner J., 2010, *MNRAS*, 405, 1375
- Lykawka P. S., Horner J., Jones B.W., Mukai T., 2009, *MNRAS*, 398, 1715
- Marzari, F., Scholl, H., 1998, *A&A*, 339, 278
- Milani, A., Carpino, M., Hahn, G., Nobili, A. M., 1989, *Icarus*, 78, 212
- Milani, A., Knezević, G., Novaković, B., Cellino, A., 2010, *Icarus*, 207, 769
- Minton, D. A., Malhotra, R., 2011, *Aj*, 732, 53
- Morais, M. H. M., Namouni, F., 2013, *MNRAS*, 436, L30
- Morbidelli, A., Brasser, R., Gomes, R., Levison, H. F. & Tsiganis, K., 2010, *Astron. J.*, 140, 1391
- Namouni, F., Murray, C. D., 1999, *Icarus*, 137, 293
- Namouni, F., Murray, C. D., 2000, *CeMDA*, 76, 131
- Nesvorny, D., Morbidelli, A., 1998, *Aj*, 116, 3029
- Rivkin, A. S., Binzel, R. P., Howell, E. S., Bus, S. J. and Grier, J. A., 2003, *Icarus*, 165, 349
- Rivkin, A. S., Trilling, D. E., Thomas, C. A., DeMeo, F., Spahr, T. B. & Binzel, R. P., 2007, *Icarus*, 192, 434
- Robutel, P., Gabern, F., Jorba, A., 2005, *CeMDA*, 92, 53
- Sándor, Zs., Érdi, B., Efthymiopoulos, C., 2000, *CeMDA*, 78, 113
- Schwarz, R., Dvorak, R., Süli, Á., Érdi, B., 2007, *A&A*, 474, 1023
- Schwarz, R., Dvorak, R., 2012, *CeMDA*, 113, 23
- Tabachnik, S. A., Evans, N. W., 2000, *MNRAS*, 319, 63
- Tsiganis, K., Dvorak, R. & Pilat-Lohinger, E., 2000, 354, 1091
- Warner B. D., Harris A. W., Vokrouhlický D., Nesvorný D. & Bottke W. F. 2009, *Icarus*, 204, 172
- Wiegert, P. A., Innanen, K. A., Mikkola, S., 1998, *Astron. J.*, 115, 2604

